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# RECENT DEUTERIUM OBSERVATIONS AND BIG BANG NUCLEOSYNTHESIS: A NEW PARADIGM?

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*A new observation of  $D$  in a primordial gas cloud, made using the high resolution spectrograph at the Keck telescope, indicates an abundance  $D/H = (1.9 - 2.5) \times 10^{-4}$  [1]. Since deuterium is destroyed by stars, and the predicted Big Bang Nucleosynthesis (BBN) abundance falls monotonically with increasing baryon density, deuterium places a reliable upper limit on the baryon density of the universe. Because the new measurement is substantially larger than previous, galactic estimates, it would force a reassessment of BBN predictions— if it is confirmed. Using a new BBN Monte Carlo code and analysis technique [2] we derive constraints implied by a lower limit of  $D/H = 1.9 \times 10^{-4}$ . We find  $\Omega_B \leq .0068 h^{-2}$ , which is definitively incompatible with baryonic halo dark matter. We also explore implications of combining the  $D$  measurement with other light element abundances.  ${}^7\text{Li}$  provides a lower bound,  $\Omega_B \geq .004 h^{-2}$ . Also, the initial  ${}^4\text{He}$  mass fraction ( $Y_p$ ) would have to be less than 23.5%, assuming 3 light neutrino species—in good agreement with present best fits. Finally, observational upper limits of  $Y_p \leq 24\%$  and  ${}^7\text{Li}/H \leq 2.3 \times 10^{-10}$  would allow the number of neutrinos to be as big as 3.9.*

Over the past decade the constraints derived from BBN analyses have become almost uncomfortably stringent. The vast improvement in the measured neutron half-life [3] has dramatically reduced uncertainties in the predicted  ${}^4\text{He}$  abundance, for example. As a result, the upper limit one might derive on  $\Omega_B$  using  ${}^4\text{He}$  abundance constraints has marched downward as estimates of the primordial  ${}^4\text{He}$  have decreased. Even the relatively recent consistent incorporation of uncertainties in the analysis [4, 5] has not broadened the allowed region substantially. Perhaps the most significant observable

in constraining theory however, has been the combination  $D + {}^3\text{He}$ . Under the assumption that this combination cannot have increased since it was initially created, the claimed upper limit of  $10^{-4}$  on the  $(D + {}^3\text{He})/\text{H}$  fraction places a lower limit on  $\Omega_B$  which is sufficiently large that the predicted  ${}^4\text{He}$  abundance, which increases with  $\Omega_B$ , is large enough to exceed some “ $2\sigma$ ” estimates of the allowed upper limit on  $Y_p$ .

Recently, we re-examined BBN constraints [2] and argued that they were even stronger than previous estimates, due to several features:

- (a) The world average for the neutron half-life ( $\tau_N = 889 \pm 2.1\text{sec}$ ) has an uncertainty which is almost twice as small as that used in previous analyses.
- (b) Improvements in the BBN code, including a finer integration of the nuclear abundances, and the inclusion of  $M_N^{-1}$  effects[6], result in a new  $\eta_{10}$ -independent correction of  $+0.0031$  to  $Y_p$ . All corrections applied to date thus combine to produce a net correction to  $Y_p$  of  $+0.0006$ .
- (c) Incorporating the fact that predicted elemental abundances are correlated means that determining limits on cosmological parameters by using the different abundances independently, as had been the case, is not consistent. In our own Monte-Carlo analysis, we demonstrated that simultaneous use of constraints on both  ${}^4\text{He}$  and  $D + {}^3\text{He}$  could dramatically reduce the number of models which were allowed at the “ $2\sigma$ ” level.

The BBN constraints we derived on the basis of these results, using the assumption that  ${}^4\text{He} < 24\%$  and  $(D + {}^3\text{He})/\text{H} < 10^{-4}$ , were extremely tight. In particular, a  ${}^4\text{He}$  abundance of less than  $23.8\%$  was shown to be inconsistent with these limits. This value was uncomfortably close to the claimed

upper limit on  $^4\text{He}$  . In addition, we demonstrated that greater than 3.04 effective light neutrino species in the relativistic gas at the onset of BBN was ruled out. This constraint is more severe than it might first appear, as even a light sterile right handed neutrino in a minimally extended standard model contributes more than this.

Of course, the weakest link in such an analysis is the assumed light element abundance. Measurements of  $^4\text{He}$  , for example, are mostly indirect, and subject to large systematic uncertainties. As a result, we argued that our refined BBN analysis might just as well suggest the need for revision of the light element abundance estimates inferred from observation instead of arguing for or against new nonstandard physics.

The new claimed observation, by Songaila *et al*, of deuterium in a primordial gas cloud, at a level  $(\text{D} + ^3\text{He})/\text{H} = 1.9 - 2.5 \times 10^{-4}$  is particularly exciting in this regard. It has long been argued that any present measurement of D provides a lower limit on its primordial abundance because D is so fragile that it is easily destroyed in stars. Previously quoted abundance estimates of  $10^{-5}$  led to a firm upper bound on  $\eta_{10} < 8$  (defined by  $\Omega_B = .0036h^{-2}(T/2.726)^3\eta_{10} \times 10^{10}$ , where  $T$  is the microwave background temperature today, and  $h$  defines the Hubble parameter  $H = 100h \text{ km}/(\text{Mpc sec})$ ), which clearly established that baryons could not close the universe. The present observation, an order of magnitude larger, is also a factor of two greater than the previous upper limit on the combination  $\text{D} + ^3\text{He}$  . As a result, the new constraints one can derive on  $\Omega_B$  will be much more severe. In addition, as we shall show, this changes the way we combine elemental

abundance limits to get constraints on cosmology and particle physics.

The system explored by Songaila *et al* in principle provides a direct probe of unprocessed D. Nevertheless, the present measurement is not yet definitive, and could be subject to systematic errors [1]. For example, an intervening gas cloud moving relative to the first cloud at a small radial velocity could produce H absorption lines which are shifted, and could mimic D absorption lines. Moreover, while one might expect the D abundance in the primordial clouds would exceed that in the galaxy, it is not clear how the large value obtained can be reconciled with previous galactic estimates .

Caveats notwithstanding, because of its potential importance for altering BBN constraints it is worthwhile to examine just how these constraints would change based on the present measurement. Having just updated our BBN analysis, it seemed an opportune time to examine this situation, and we present our results below. While the authors of [1] point out that at worst their observation provides a conservative upper bound on D, we argue here that it is appropriate, from the point of view of BBN to use the lower limit of  $1.9 \times 10^{-4}$  on the D fraction as a *lower limit* on the primordial deuterium abundance. If their result is correct, the primordial D abundance must exceed this value, since it can only be destroyed by processes since BBN. If their result is in error, then it is not clear that the old upper limit on D +  $^3\text{He}$  should be abandoned just because it is less conservative.

We find that not only is the new upper limit on  $\Omega_B$  implied by the new D value is low enough to convincingly rule out baryonic dark matter, constraints on both  $Y_p$  and  $N_\nu$  are also significantly altered. Finally,  $^7\text{Li}$  now provides

a lower bound on  $\Omega_B$ , which while somewhat uncertain, is compatible with  $\Omega_B$  comparable to the luminous baryon abundance today.

Our Monte Carlo analysis proceeds as follows: we allow input uncertainties corresponding to measurement uncertainties in the BBN nuclear reactions. Each rate is determined using a Gaussian distributed random multiplier centered on unity, with a  $1 - \sigma$  width based on that quoted in [5]. For the rates with temperature dependent uncertainties the original uniformly distributed random number is saved and mapped into a new gaussian distribution with the appropriate width at each time step. For each value of  $\eta_{10}$  we then ran 1000 BBN models. ( see [2] for details).

In figure 1 we display the predicted ranges for D,  $^4\text{He}$ , and  $^7\text{Li}$  for the range  $1 < \eta_{10} < 2$ , along with the new D observational lower limit, and the claimed upper limits on  $^4\text{He}$  and  $^7\text{Li}$ , assuming 3 light neutrino species. For each value of  $\eta_{10}$  all 1000 model predictions are shown, along with the median predictions, the one-side  $2\sigma$  upper (lower) limit for D ( $^7\text{Li}$ ), and the symmetric  $2\sigma$  range for each element. The one-side limits occur when less than 50/1000 models fell below(above) the limits, while the symmetric limits encompass the central 950/1000 predictions. The D and  $^7\text{Li}$  limits imply the allowed range  $1.13 < \eta_{10} < 1.87$ , which leads to the constraints on  $\Omega_B$  quoted above. (If one were to put a upper limit on primordial D of  $2.5 \times 10^{-4}$ , derived from the new D observation alone, the lower limit on  $\Omega_B$  would increase by 15 % from the more conservative limit quoted above using  $^7\text{Li}$ )

In figure 2, we display the predicted  $^4\text{He}$  vs D abundances for the upper limit  $\eta_{10} = 1.87$ , assuming three species of light neutrinos. Here the clear

anti-correlation between these abundances is clear. Utilizing this result, we see that for the region above the allowed D lower limit, the maximal value of  ${}^4\text{He}$  is near 23.5%. This is a complete reversal of the previous BBN limits, which put a lower bound on  ${}^4\text{He}$ . What is perhaps more interesting is that this new upper bound is far more consistent with the best fit estimates of  $23 \pm 1\%(2\sigma)$  which are often applied to  ${}^4\text{He}$ .

The role played by varying the number of neutrinos is quite different than it was when one combined an upper limit on  $\text{D}+{}^3\text{He}$  with an upper limit on  ${}^4\text{He}$ , aside from a relaxed upper bound on  $N_\nu$  due to the lower predicted  ${}^4\text{He}$  fraction in this range of  $\eta_{10}$ . Before, raising the number of neutrinos tightened BBN constraints, but now it can actually relax them. In order to give the most conservative limits on  $\eta_{10}$  we must allow the effective number of neutrinos to vary from 3, to account for possible new particles contributing to the radiation gas during BBN at the fraction of a neutrino level.

The point is that in the range of  $\eta_{10}$  of interest, increasing  $N_\nu$  monotonically increases all elemental abundances. At  $\eta_{10} = 1.8$  an increase of  $N_\nu$  of 1 produces an increase of 5% in  $Y_p$ , 15% in  $\text{D}/\text{H}$  and 23% in  ${}^7\text{Li}$ . This implies that an increase in the effective number of relativistic species will increase the upper limit on  $\Omega_B$  because the predicted D abundance will increase. However, at some point the upper bound on  $\Omega_B$  from  ${}^4\text{He}$  (or  ${}^7\text{Li}$ ) will eclipse that from D. By varying the number of neutrinos, we find the maximum allowed value of  $\eta_{10}$  is 1.91, obtained for 3.4 effective neutrino species.

Increasing the number of neutrino species beyond 3.9 results in violation of the observational limits for any range of  $\eta_{10}$ , as shown in figure 3, where we

plot the number of models, out of 1000, allowed by *simultaneously* employing the  $^4\text{He}$  and  $^7\text{Li}$  limits, as a function of  $\eta_{10}$  for both 3.9 and 4.0 neutrinos. Clearly, any further relaxation of either limit would weaken the bound, allowing 4.0 neutrinos. This relaxed limit on the number of effective light neutrinos is quite significant for model building, as it allows breathing room for new physics. For example, an extra scalar particle in thermal equilibrium at the BBN era would contribute about .55 neutrinos.

As we have illustrated, the new D measurement could be quite exciting for cosmology. If confirmed, it will change the way we use primordial element abundances to get cosmological and particle physics constraints, as we have shown in the new confidence ranges we have derived. In some sense, the new cosmological constraints would be satisfying. The allowed range of  $\Omega_B$  would overlap with the amount of visible matter in the Universe. What you see may be what you get, a result which has some attraction. In addition, the  $^4\text{He}$  fraction can be much closer to what some people have been claiming, and the constraint on plausible extra particles in the radiation gas during BBN is relaxed. At the very least, if the new result is confirmed, the evidence for non-baryonic dark matter will have increased dramatically, and the possible confrontation with MACHO searches will be interesting to watch.



## References

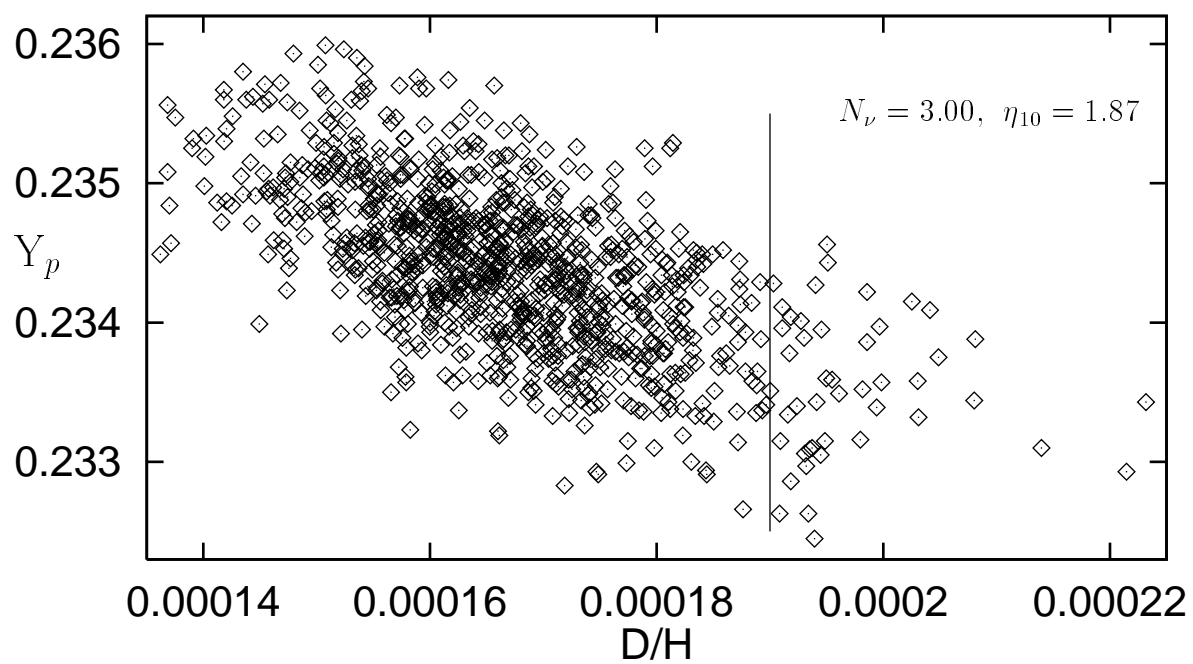
- [1] A.Songaila, L.L.Cowie, C.J.Hogan and M.Rugers, *Nature* **368**, 599 (1994)
- [2] P.Kernan and L.Krauss, astro-ph 9402010, *to appear in* Phys.Rev.Lett.
- [3] Part. Data Group, *Review of Particle Properties*, Phys.Rev.**D45** (1992)
- [4] L.M.Krauss and P.Romanelli, *Ap.J.*, **358**, 47 (1990)
- [5] M.K.Smith, L.H.Kawano and R.A.Malaney, *Ap.J.Supp.* **85**, 219 (1993)
- [6] D.Seckel, Bartol Preprint BA-93-16 hep-ph/9305311.

## Figure Captions

Figure 1: BBN Monte Carlo predictions as a function of  $\eta_{10}$  for  ${}^4\text{He}$ , D, and  ${}^7\text{Li}$ . Shown are symmetric 95% confidence limits on each elemental abundance, as well as one sided 95% upper (lower) limits for D ( ${}^7\text{Li}$ ). Also shown are observational limits, including the new D lower limit, we use.

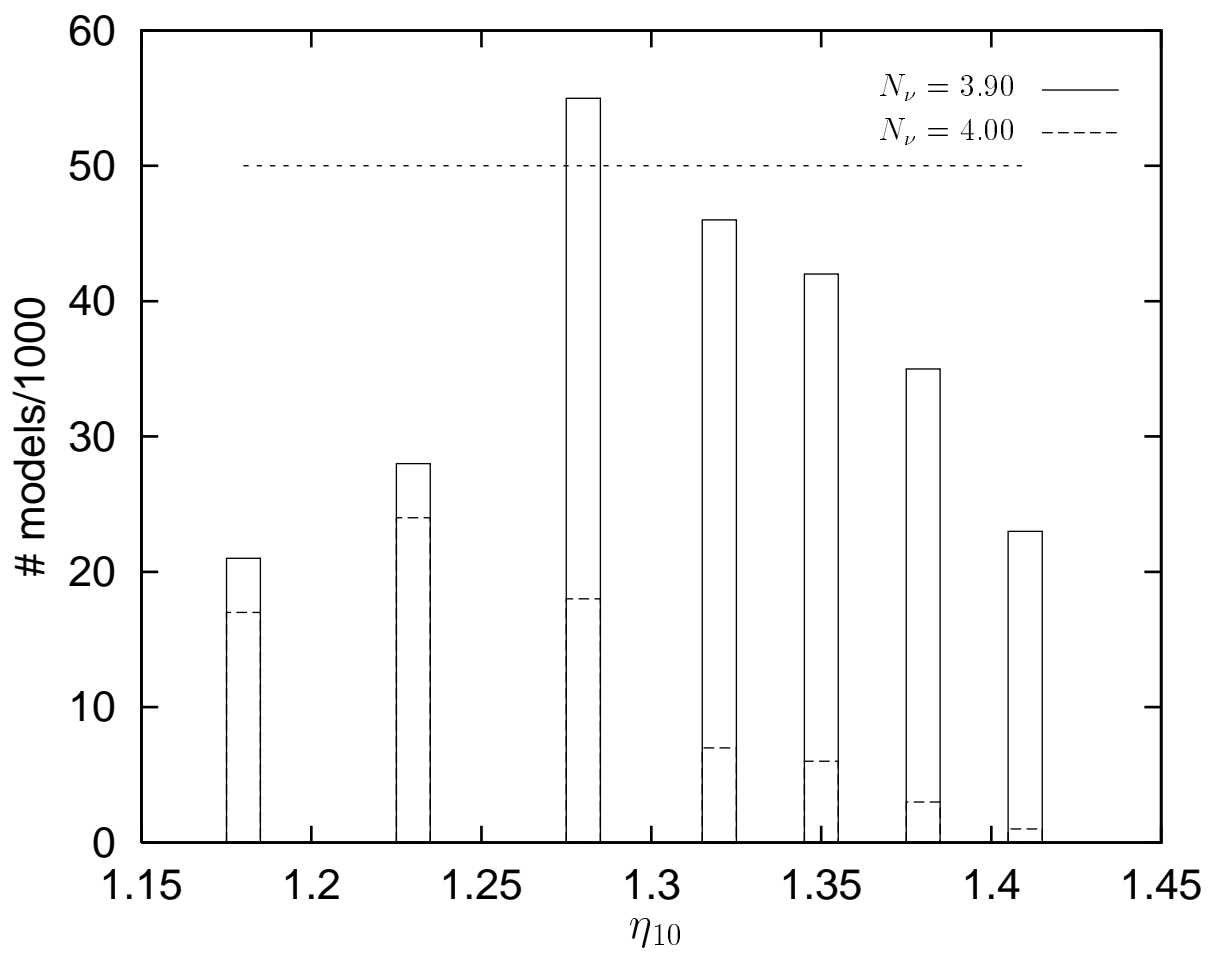
Figure 2: 1000 Monte Carlo BBN predictions for  $Y_p$  and D/H abundances. The vertical line corresponds to a lower limit on D/H of  $1.9 \times 10^{-4}$

Figure 3: Number of models (out of 1000 total models) which simultaneously satisfy the constraints  $Y_p \leq 24\%$  and  ${}^7\text{Li}/\text{H} \leq 2.3 \times 10^{-10}$ , for 3.9 and 4.0 neutrinos.



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This figure "fig1-3.png" is available in "png" format from:

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